TABLE 1. Recent development of TPV cells for waste heat recovery application.

Ref.	Year	Material	E_g (eV)	Temperature (ºC)	Highlights	Challenges
[72]	2020	Bi_2Te_3/Si	0.15-0.17	27-207	• Demonsrated a Bi_2Te_3/Si TPV cell by using p-type single-crystalline Si wafer. • Reported an optimal thickness of Bi_2Te_3 thin films around 310 nm.	• Absence of tunneling junction at the interface prevents generated holes to pass through, reducing the output current. • Possible defects in Bi_2Te_3 thin films.
[73]	2019	GaSb	0.72	1000	• Demonstrated a GaSb TPV prototype with ~1.5% energy efficiency under 1000 ºC. • Can be used effectively with higher waste heat temperatures.	• Low cell efficiency due to high-temperature exposure. Installation of a cooling system is needed. • The gap distance between the TPV cell and source of radiation affects cell performance.
[71]	2019	GaInAsSb/GaAs	0.53	800	• The metamorphic buffer layer approach in molecular beam epitaxy process enables high quantum efficiency and reduces mass production cost.	• Poor sidewall resistivity • Low shunt resistance
[66]	2018	InAs	0.35	500-1000	• Reported a 3.6% power conversion efficiency under 950 ºC thermal sources. • Demonstrates higher performance when lowering the cell temperatures	• Performance strongly dependent on the dark current of the TPV cell. • Limited hole charge carrier lifetime causes reduction in EQE
[69]	2017	Interband cascaded InAs/GaSb/AlSb	0.4	527	• Three-stage devices shows higher conversion efficiency as compared to two-stages that is 9.6% and 6.5%, respectively.	• High series resistance due to the sidewall leakage • Device design and fabrication need improvisation.
[70]	2016	Lead sulfide colloidal quantum dots	0.75	800	• Demonstrated a power conversion efficiency of 2.7% • Good performance stability up to 140 ºC.	• Improvement of well-passivated colloidal quantum dots films. • Elimination of less stable organic ligands.
[65]	2015	$InAs/InAs_{0.6}Sb_{0.13}P_{0.26}$	0.32	345-950	• An efficiency of 3% was recorded under blackbody temperature of 950 ºC. • Able to operate at 345 ºC when using 65 single cells in a series interconnection.	• High series interconnection resistance • Optimization of top contact electrode is needed.

of TPV performance due to surface phonon-polaritons in graphene and boron-nitride. Overall, these studies provide important insight into the effect of parasitic phonon-polariton on TPV cell performance.

Recent development in TPV cell aims to achieve higher conversion efficiency by converting low-temperature waste heat into electricity. According to the literature, numerous materials with narrow bandgap have been widely explored to find the possibilities of integrating these materials with such low-radiant energy sources. Licht *et al.* [78] reviewed on the performance of narrow bandgap materials for waste heat harvesting applications. Nevertheless, the incorporation of narrow bandgap material comes with certain challenges. For example, the dark saturation current in TPV cell is increased by narrowing down the bandgap energy due to the recombination effect across the bandgap [2]. More researches on the effect of dark current are essential to provide a better insight on the factors affecting the TPV cell performance. Other than the cell bandgap, Feng *et al.* [79] investigated the effect of near-field TPV system on the TPV cell dark current parameter. It was found that the domination of evanescent waves developed from the total internal reflection and surface polariton increases the saturation current due to radiative recombination. Hence, both of the cell bandgap and the vacuum gap distance are the tradeoffs for obtaining high performance TPV cell with low dark current.

IV. TPV IMPLEMENTATION IN WASTE HEAT HARVESTING APPLICATION

There are several approaches of implementing TPV device for the waste heat recovery application. In particular, the temperature from industrial waste heat has been reported in the range from 30 °C to 1650 °C, according to US Department of Energy [80]. For instance, Fraas *et al.* [13] demonstrated a TPV system with high power density for iron and steel industrial waste heat recovery at 1100 °C by sandwiching the TPV devices between hot steel billets to capture most of the radiant waste heat energy. Additionally, the TPV device can possibly be deployed to any semi-transparent furnace areas as well as integrating TPV cells between the hot surface and insulators in glass industries [81].

A. HYBRID TPV SYSTEM

Recently, researchers have spurred research efforts in harvesting waste heat through a hybrid TPV power generation system. The advantage of a hybrid TPV system includes exposure to high-temperature waste heat in continuous

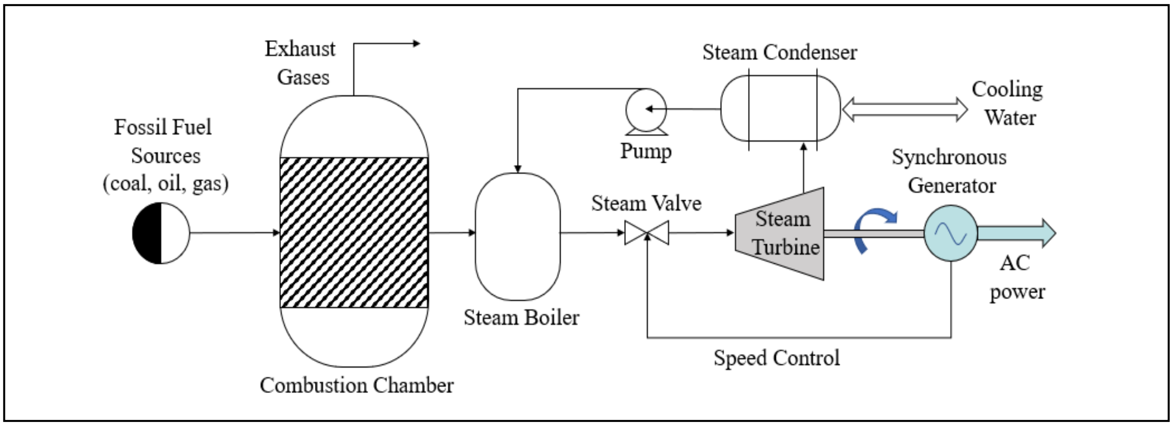

FIGURE 3. The block flow diagram of a typical fossil fuel-fired, thermal power plant.

operation with a steady condition. Thermoelectric generator (TEG), Brayton-Rankine combine cycle (TBRC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), direct carbon fuel cell (DCFC), and direct carbon SOFC (DC-SOFC) are among the reported systems which are paired with TPV system. For example, Chubb and Good [32] investigated a TPV-TEG hybrid system and found that the system generates larger output power density as compared to stand-alone TEG or TPV system. Besides, the integration of TPV system at the exhaust waste heat of SOFC outperforms other SOFC-based coupling systems [82], [83].

Nowadays, many reported hybrid TPV systems demonstrate improvement in the power output; however, to develop a high-performance hybrid system comes with several challenges. Table 2 presents the challenges in developing a hybrid TPV system.

B. TPV IMPLEMENTATION IN THERMAL POWER PLANT

A thermal power plant operates with the principle of Rankine cycle in a complex design system. Fossil fuels such as coal, natural gas and petroleum are the main energy sources which are exploited to translate water into steam through combustion process. The steam is generated either in a combustion engine or a boiler, depending on the fuel source. Heating the steam in a constant high-pressure condition produces superheated steam with high energy which rotates the blades of a steam turbine. This makes the steam to lose the energy and expand as the pressure is dropped rapidly. The residual steam is then reverted into water by condensation and recycled to the combustion chamber. The rotating steam turbine is connected with an electrical generator to convert the kinetic energy into electrical energy. Fig. 3 illustrates the process flow diagram of a typical thermal power plant.

Due to the complex Rankine cycle, a huge amount of energy is lost through the conversion process. The typical efficiency of power plants in developing countries remains around 32-35% [50]. Numerous studies have investigated both energy and exergy analyses to demonstrate complete magnitudes, location, and causes of losses in a thermal power plant [90], [91]. On top of that, significant assessment

TABLE 2. Recent development in hybrid TPV system.

Ref.	Year	Hybrid system	Operating temperature (K)	Challenges
[84]	2020	SOFC	1073	• Vacuum gap is limited to nanoscale due to the fluctuation dynamics at extreme near-field region
[85]	2019	TBRC	600 – 1000	• Expensive TPV emitter material and manufacturing
[86]	2018	DC-SOFC	1073 – 1173	• High cost of manufacturing • Challenges in fabricating efficient catalyst.
[32]	2018	TEG	~1200	• Large temperature difference between TPV and TEG system decreases the system efficiency.
[87]	2017	TEG	400 – 1400	• Performance depends on thermal characteristics (fuel-air equivalent ratio) of the burner
[88]	2017	DCFC	973	• Hybrid system performance depends on the DCFC temperature and number of slabs in DCFC
[83]	2016	SOFC	1073	• The design of SOFC current density and heat leak ratio is important to obtain high-performance hybrid system
[89]	2016	MCFC	923	• Higher operating temperature of MCFC is required to increase the hybrid system performance

of individual component efficiency can also be observed. Exergy is defined as the available potential energy that is capable of doing work but degraded in the process. However, this study will emphasize only on the energy analysis. This is because a TPV system can only harvest external heat loss of the process.

Most recently, Kumar [92] published a comprehensive review on the energy, exergy, exergoeconomic and economic analysis of different types thermal power plants. Thermal